Review for Midterm

EES 3310/5310

Global Climate Change

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Outline of Semester

Heat and Temperature

- Temperature is stable when heat is balanced
  - $F_{in} = F_{out}$ (F = heat flux)
- Radiative equilibrium:
  - F_{in} is shortwave light from sun
  - F_{out} is longwave light from earth
    - Where on earth does F_{out} come from?
  - Why is F_{in} shortwave and F_{out} longwave?
  - Equations (in W/m^2):

$$F_{\text{in}} = \frac{(1-\alpha) I_{\text{solar}}}{4} \quad \text{(Absorption)}$$

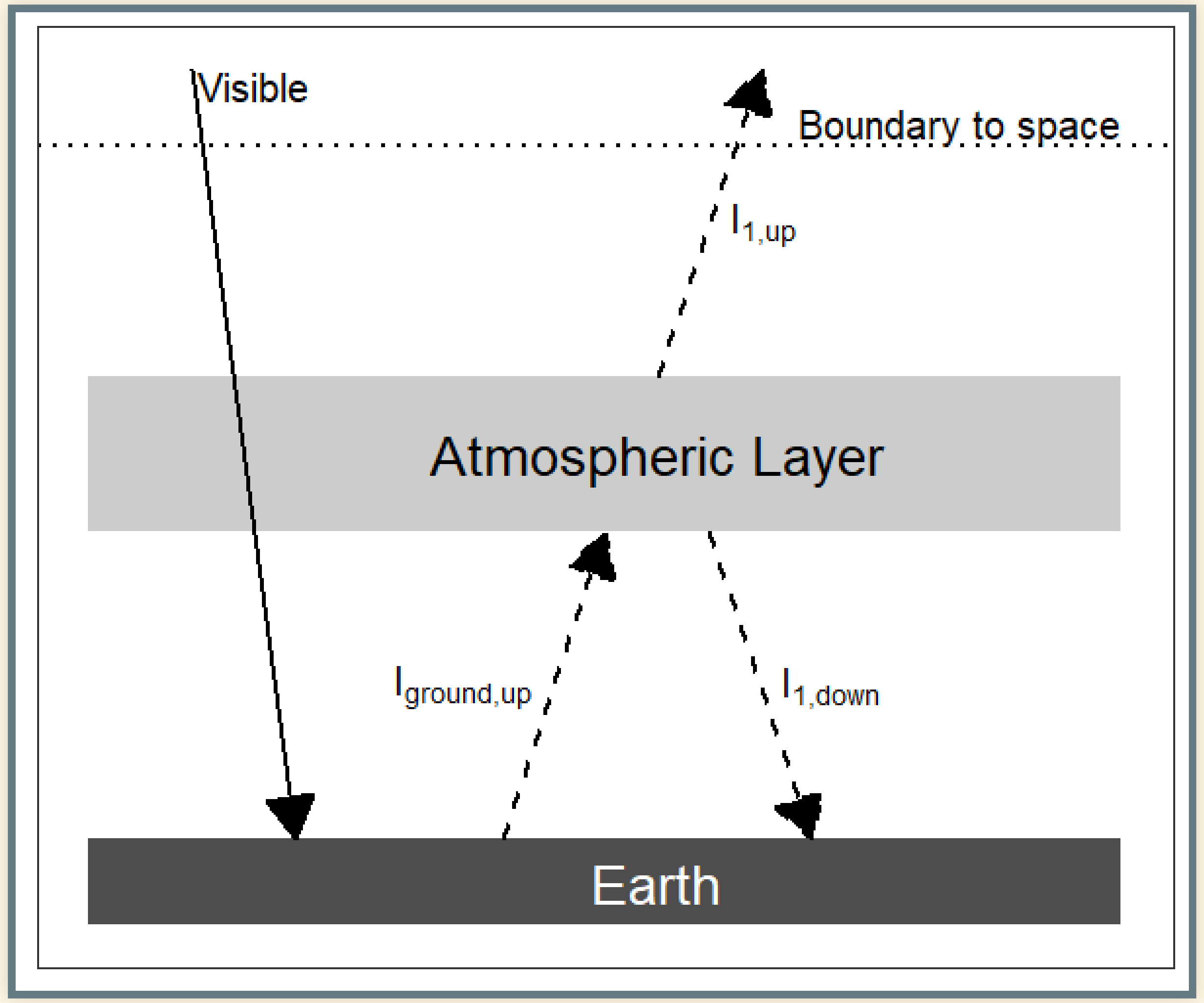
$$F_{\text{out}} = \varepsilon \sigma T_{\text{skin}}^4 \quad \text{(Stefan-Boltzmann Law)}$$

Greenhouse Effect

- No greenhouse gases: Bare-rock model

$$T = \sqrt[4]{\frac{(1-\alpha)I_{\text{solar}}}{4\varepsilon\sigma}}$$

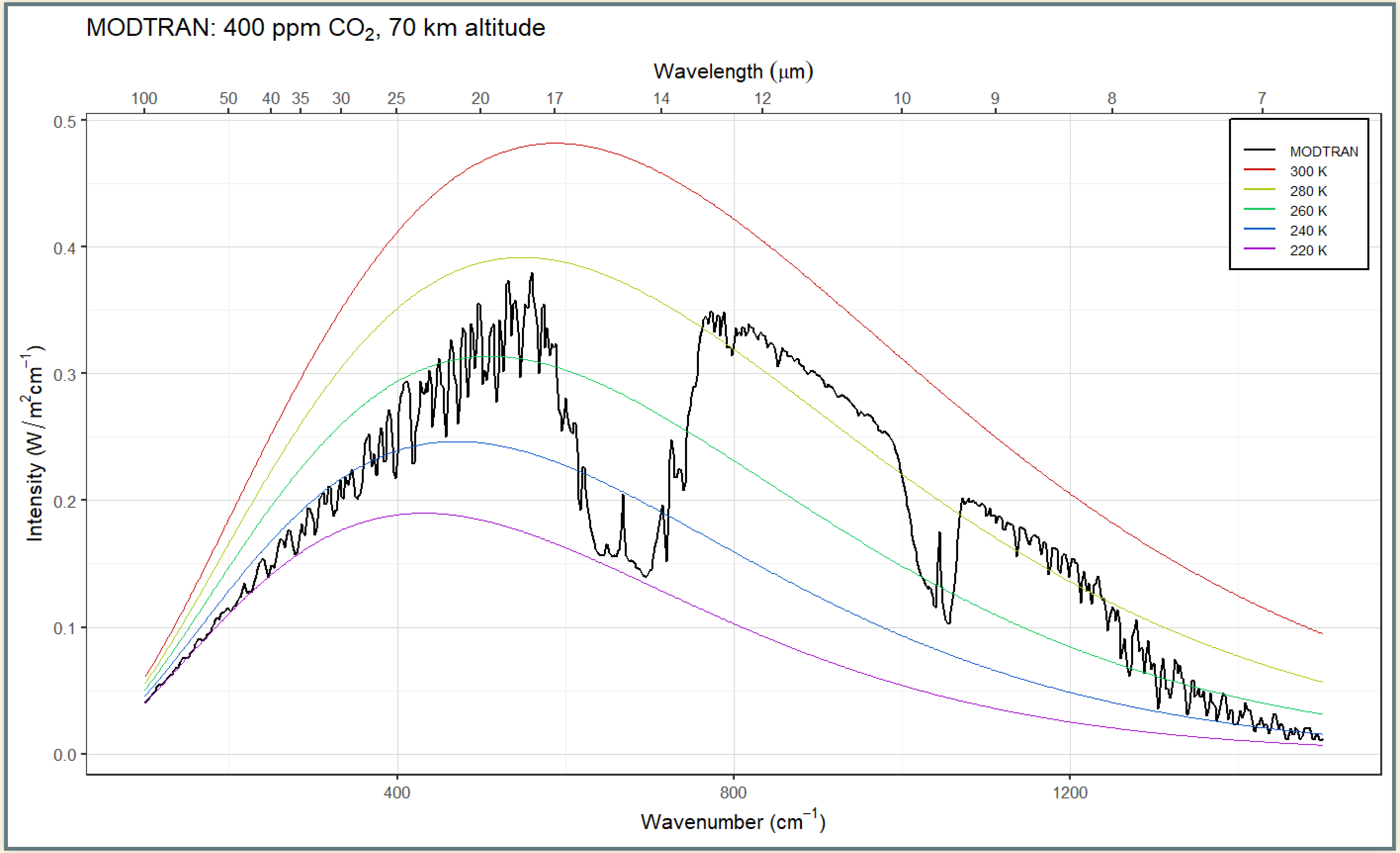
- Add greenhouse gases:
  - Simple model: Layer model ($\varepsilon = 1$ for all wavelengths)



More Realistic Greenhouse Effect

More Realistic Greenhouse Effect

- With real greenhouse gases, ε varies with wavelength:



MODTRAN:

- MODTRAN calculates *emissions* and *absorption* of longwave light in the atmosphere.
- Things that don't change during a run:
  - Heat from the sun
    - Set by "locality" of the atmosphere
  - Temperature of the ground and every layer of the atmosphere.
    - Set by "locality" of the atmosphere and "temperature offset"

Locale	I_{out} (W/m^2)	T_{ground} (K)
U.S. Standard Atmosphere	267.98	288.2
Tropical	298.67	299.7
Midlatitude winter	235.34	272.2

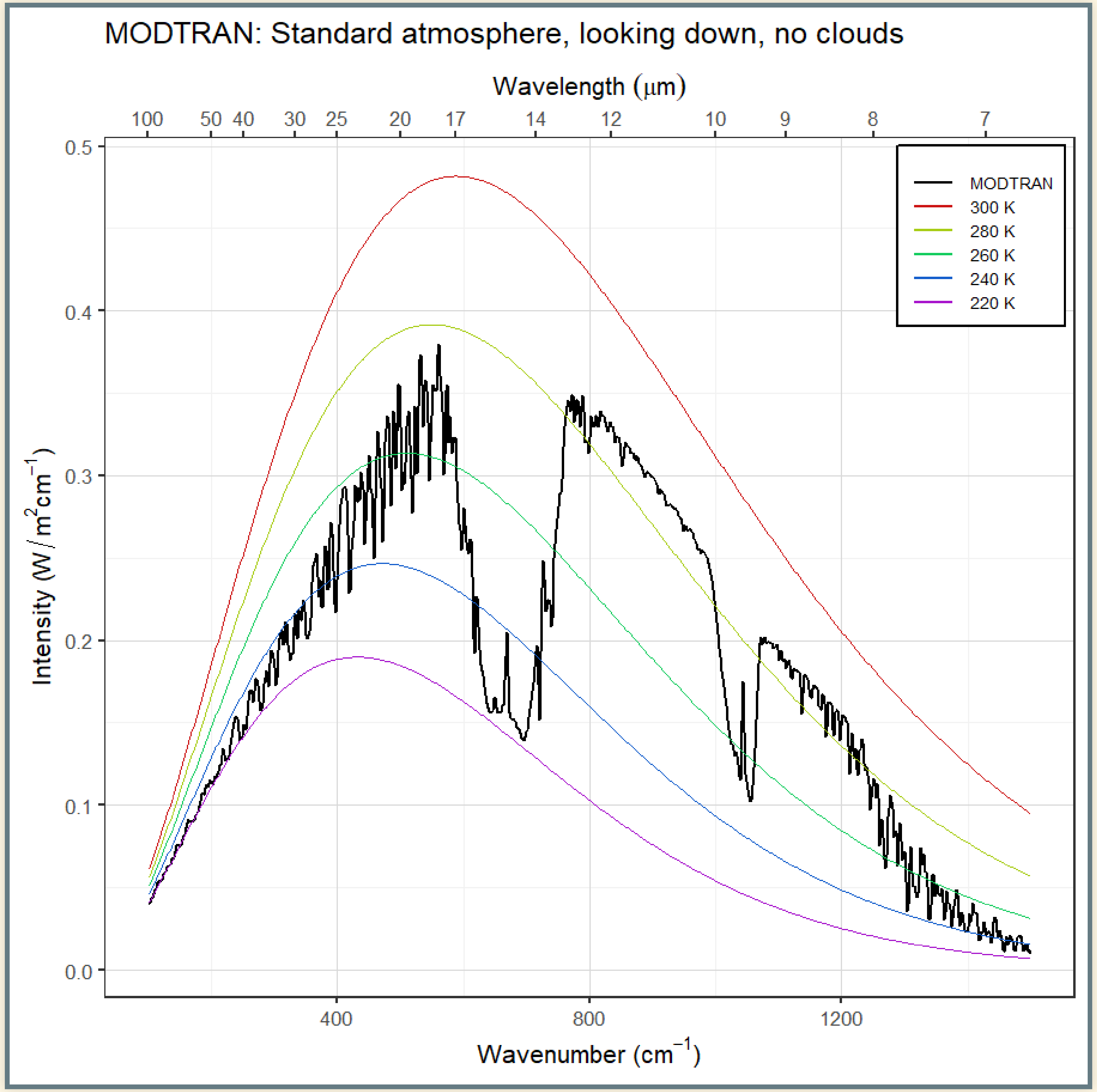
- For every wavenumber, MODTRAN calculates heat emission and absorption up and down at each layer.

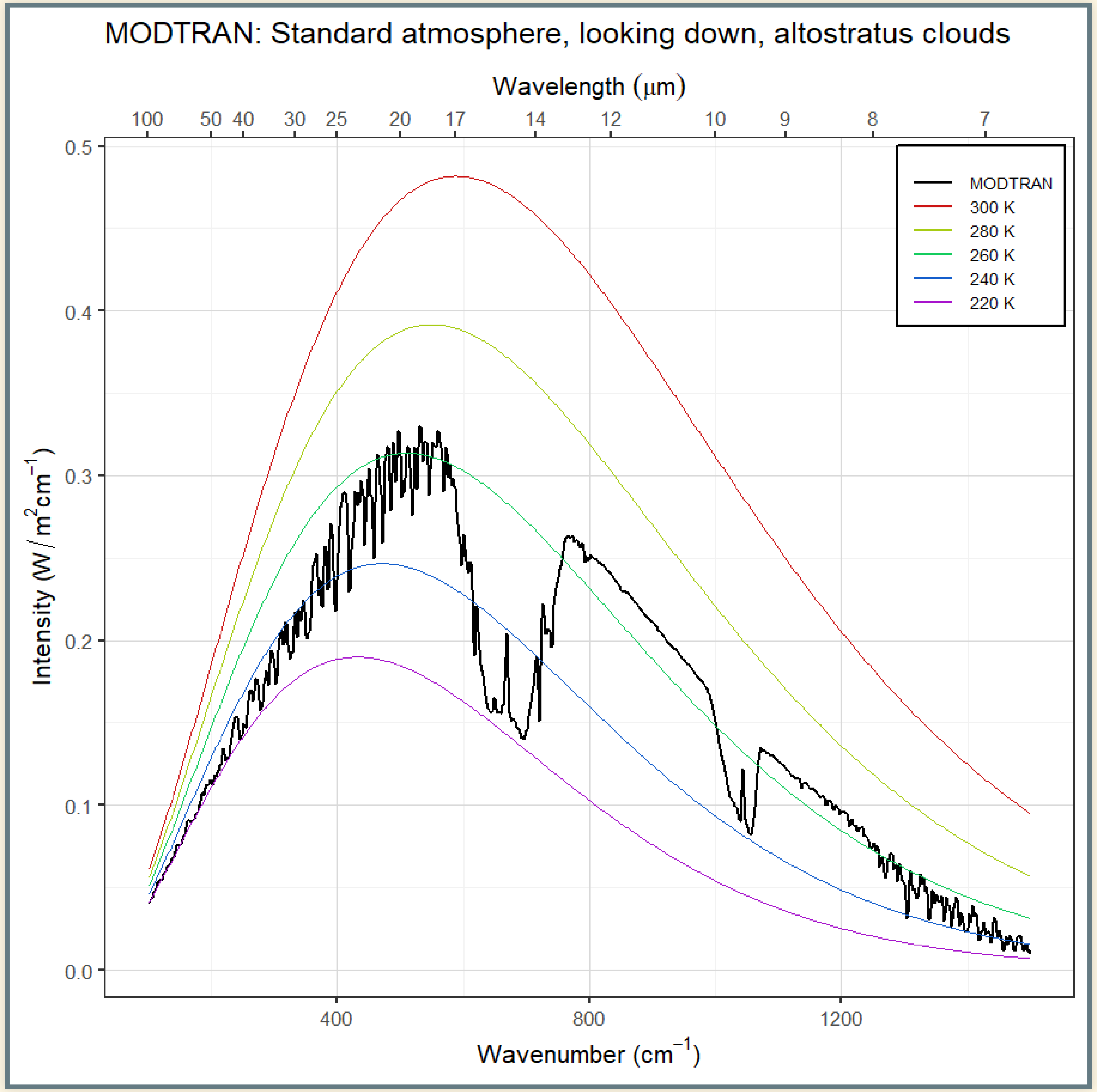
MODTRAN:

- Emissivity (ε) = absorption
  - Fraction absorbed by layer $= \varepsilon$
  - Radiation emitted by layer $= \varepsilon\sigma T^4$
- ε small (near zero):
  - Little absorption or emission.
- ε large (near one):
  - Almost all incoming radiation is absorbed
  - Emission close to black body at temperature *T*.
- ε is large for wavenumbers where greenhouse gases absorb strongly.
  - Greater concentration $\rightarrow$ larger ε
- ε is small where there is little absorption
  - Atmospheric window

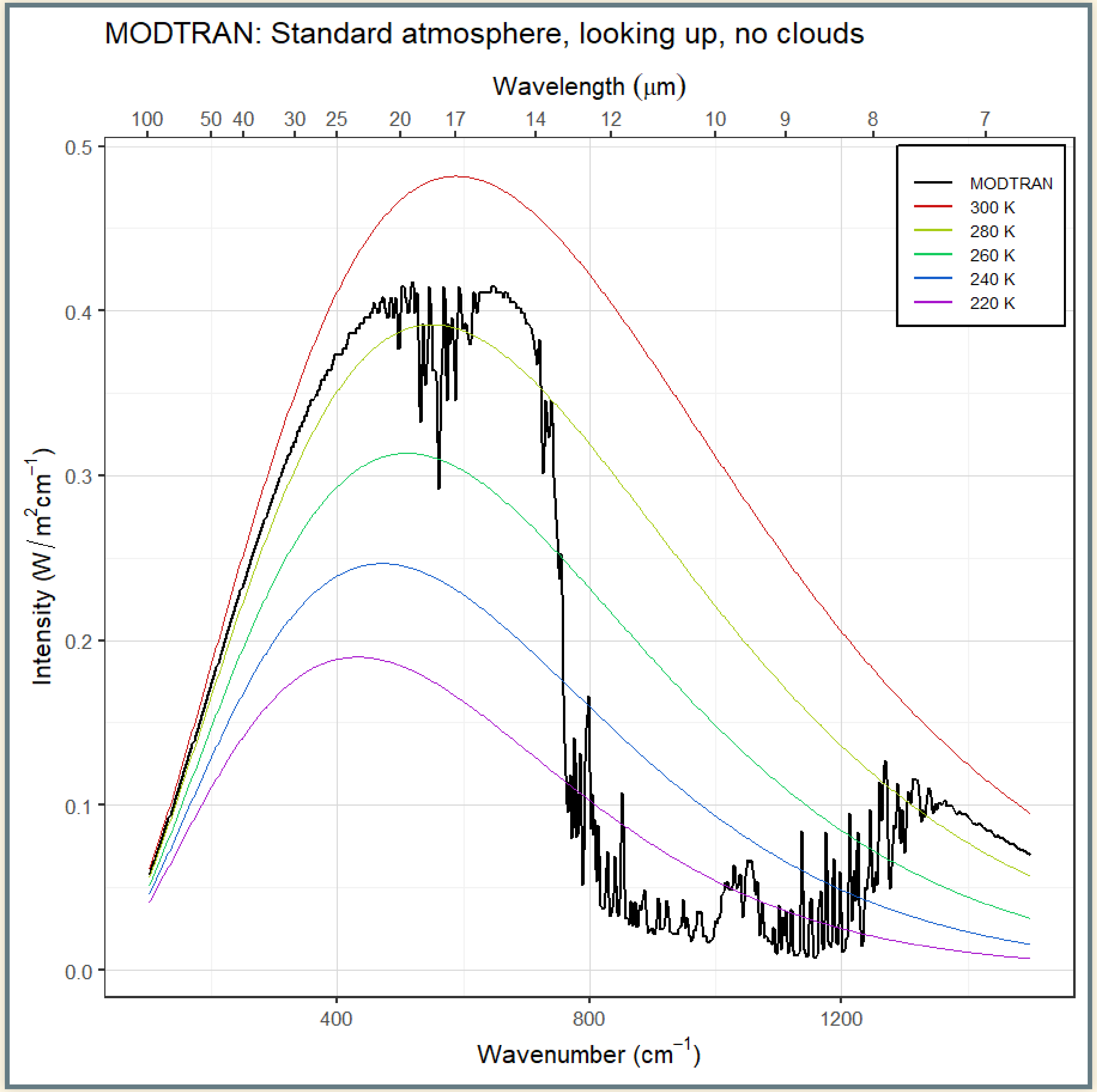
- Sensor sees emission at the temperature of the ***nearest layer*** with large ε:
- **Looking down from space:**
  - ***highest layer* with large ε**
  - In atmospheric window, that layer is near the ground
  - With clouds, it's often the top of the highest cloud
- **Looking up from ground:**
  - ***lowest layer* with large ε**
  - In atmospheric window, there's no such layer, so you see very little emission
  - With clouds, it's often the bottom of the lowest cloud

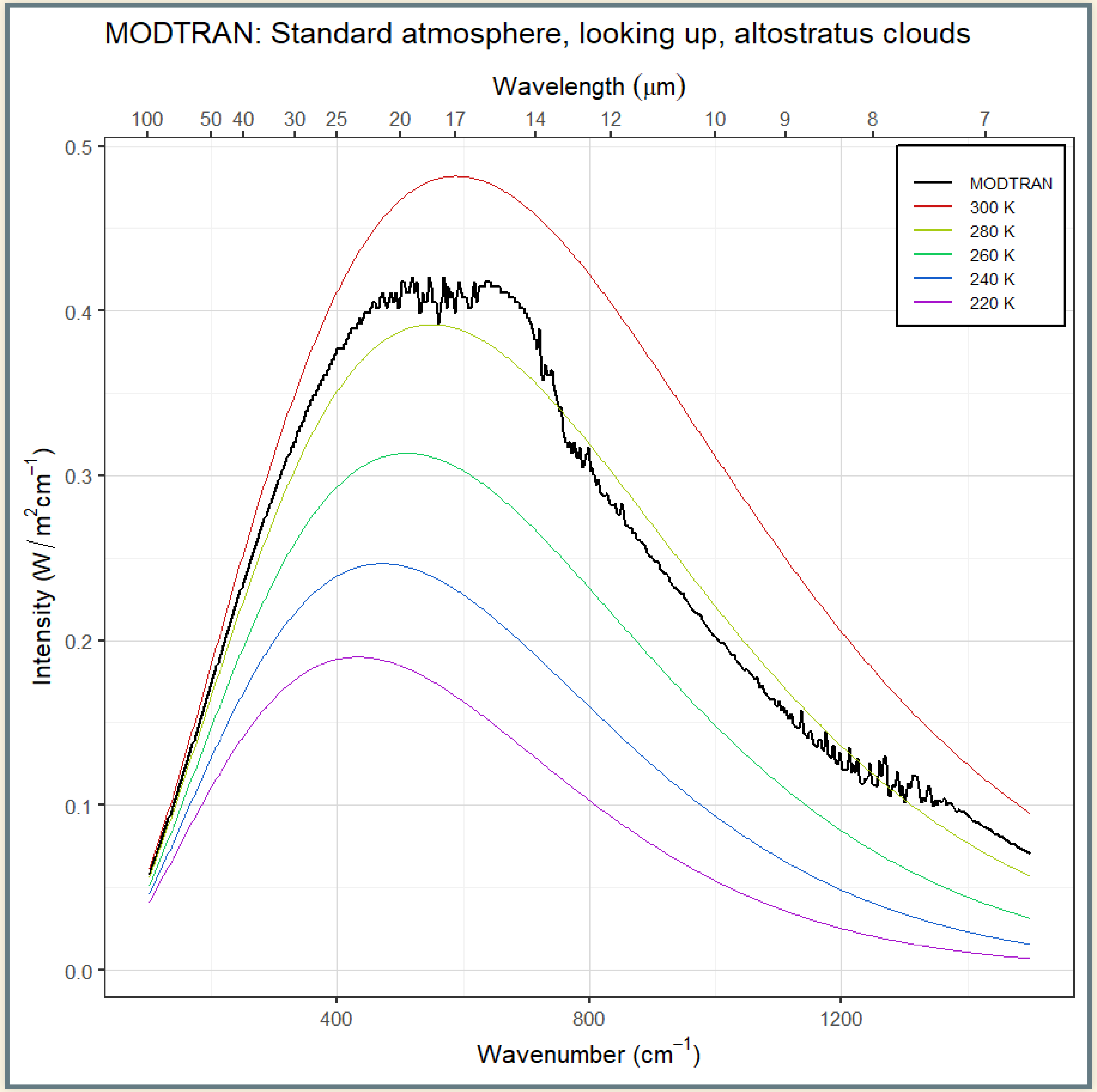
Example: Looking Down





Example: Looking Up



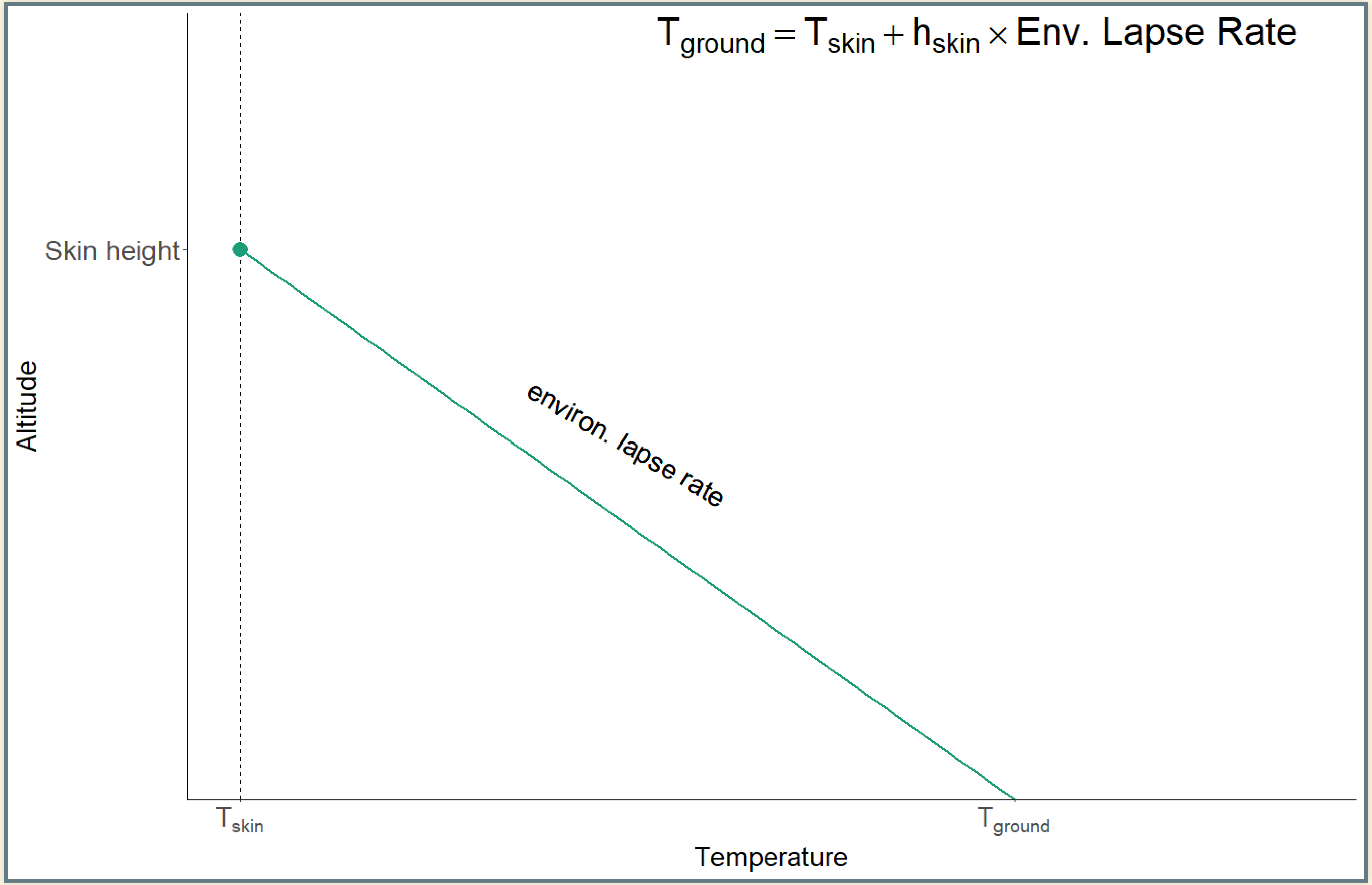


Vertical Structure of the Atmosphere

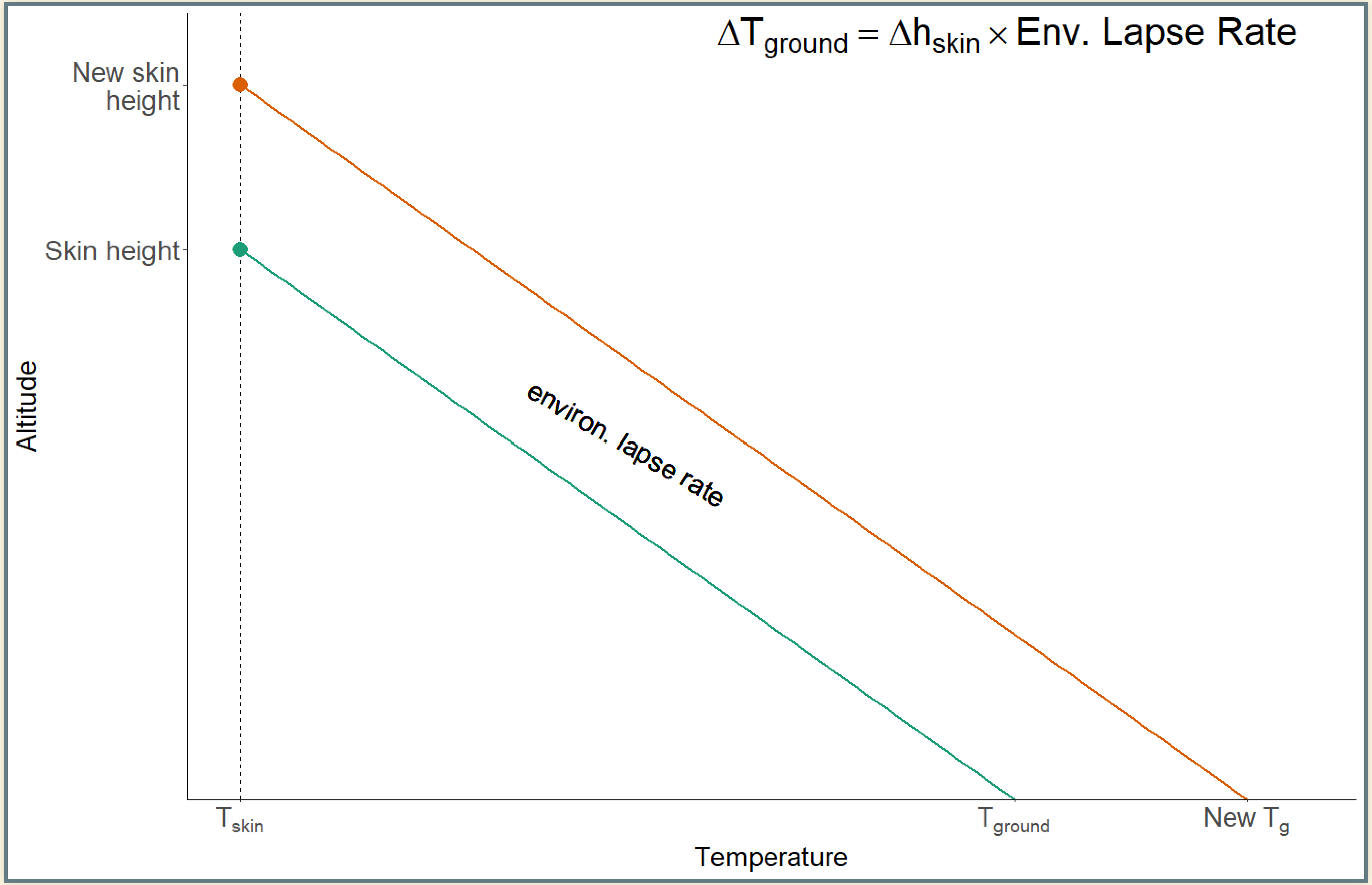
Vertical Structure of the Atmosphere

- Lapse Rate:
  - Environmental (ELR): Snapshot of actual atmosphere
  - Adiabatic (ALR): Changes as air moves up or down
  - Condition for stability: ELR < ALR
- Why does stability matter?
  - Greenhouse effect alone would make ELR very large.
    - THis would make the earth hotter than it is.
  - When ELR > ALR, convection happens
    - Convection moves heat around
    - Convection reduces ELR until atmosphere becomes stable
    - Cools surface
  - Radiative-Convective Equilibrium:
    - Convection **weakens** greenhouse effect
    - Atmosphere is just at the edge of stability
    - Greenhouse effect wants to raise ELR
    - Convection wants to reduce ELR

Vertical Structure and Greenhouse Effect



Vertical Structure and Greenhouse Effect

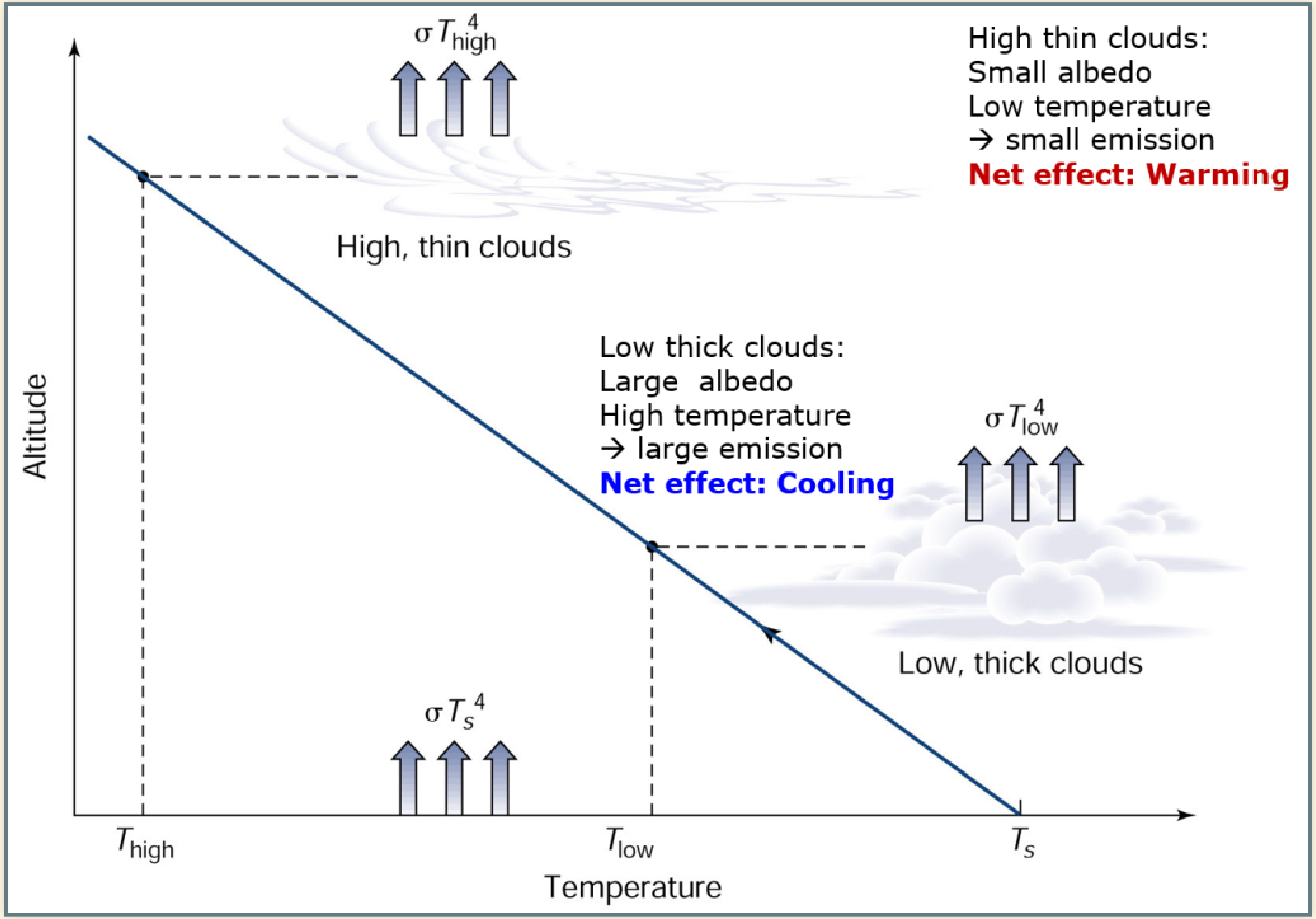


Feedbacks

Feedbacks

- Positive: amplify warming or cooling
- Negative: diminish warming or cooling
- Examples:
  - Ice-albedo (positive, fast)
  - Water vapor (positive, fast)
  - Clouds (slightly positive, fast)
  - Silicate Weathering (negative, slow)

Cloud Feedback



Silicate Weathering

- Constant CO_2 concentration:
  - Sources of CO_2 = Sinks (removal)
  - Silicate weathering = volcanic outgassing
- Raise outgassing:
  - CO_2 rises
  - Temperature rises
  - More weathering
  - Eventually … weathering = new outgassing
    - New equilibrium
    - Higher temperature

Silicate Weathering

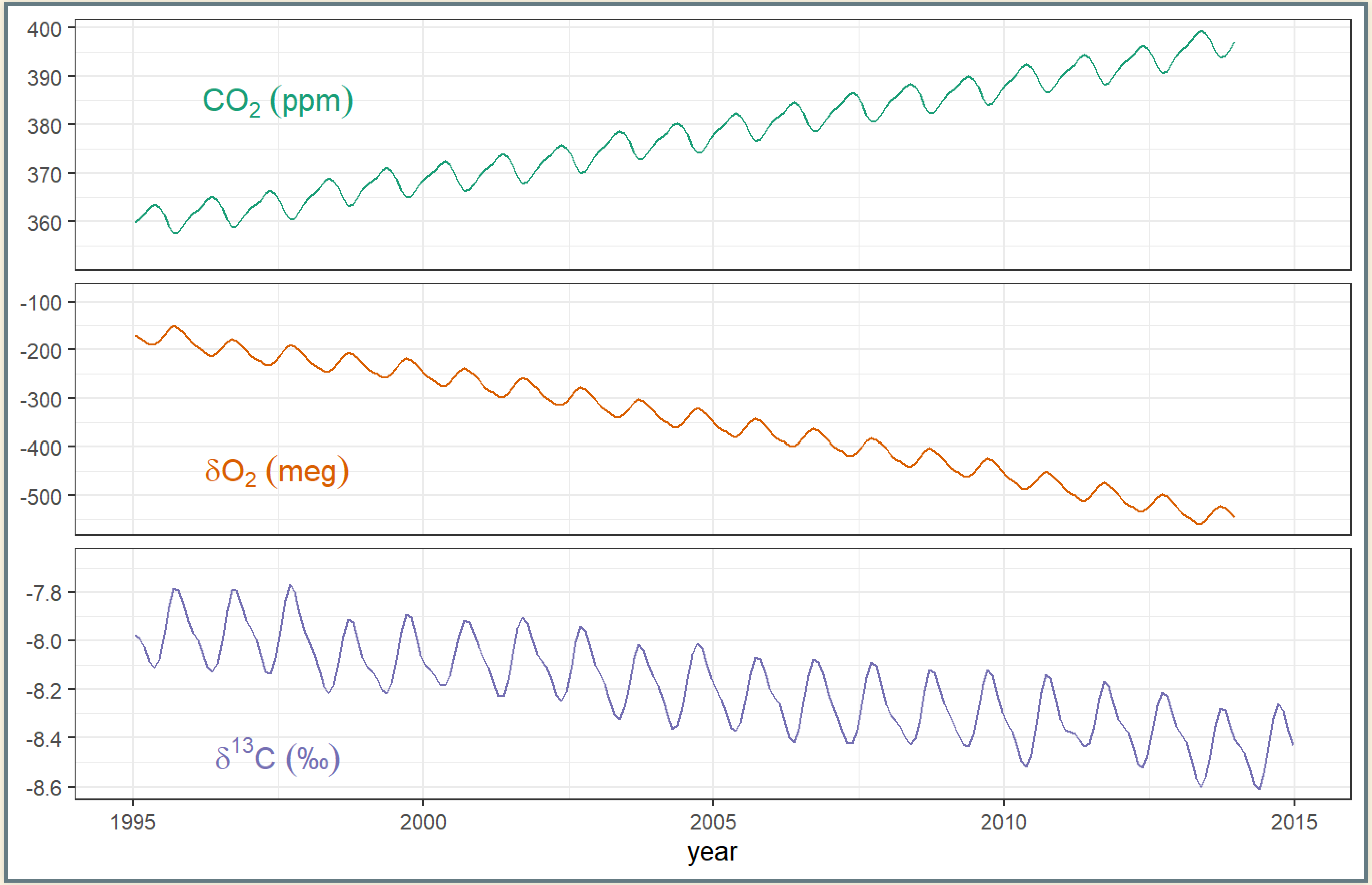
- Constant CO_2:
  - Silicate weathering = volcanic outgassing
- One-time pulse of CO_2 into atmosphere
  - Temperature rises
  - More weathering
  - Weathering > outgassing
  - CO_2 drops
  - New equilibrium when CO_2 returns to original value:
    - T returns to original value
    - CO_2 back at original value
    - Weathering = outgassing again

Geochemical Carbon Cycle

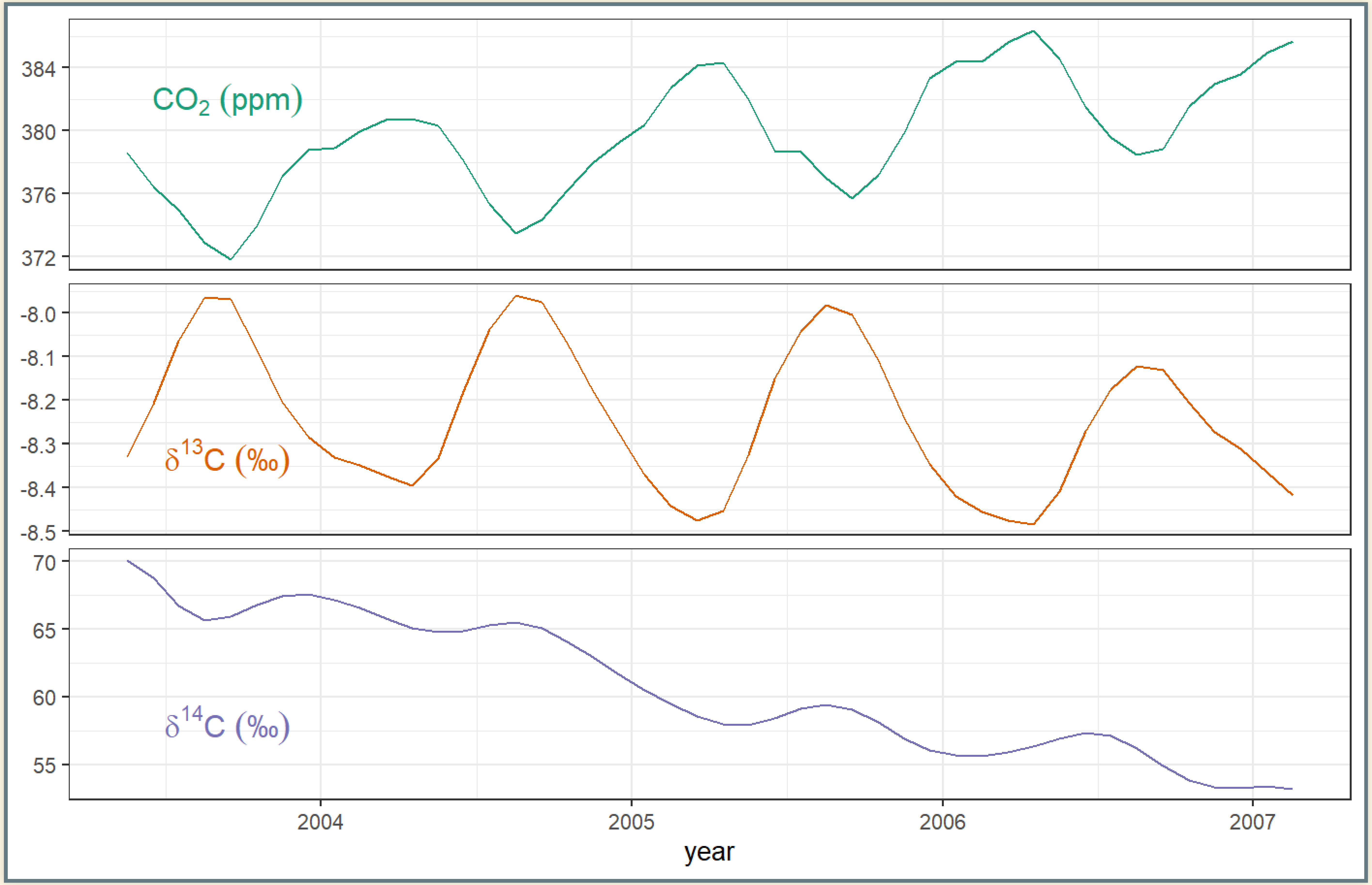
Carbon

- Oxidized vs. Reduced Carbon
- Isotopes:
  - ^{12}C, ^{13}C, ^{14}C
  - What do they tell us?
- What is the evidence that rising CO_2 comes from fossil fuels?

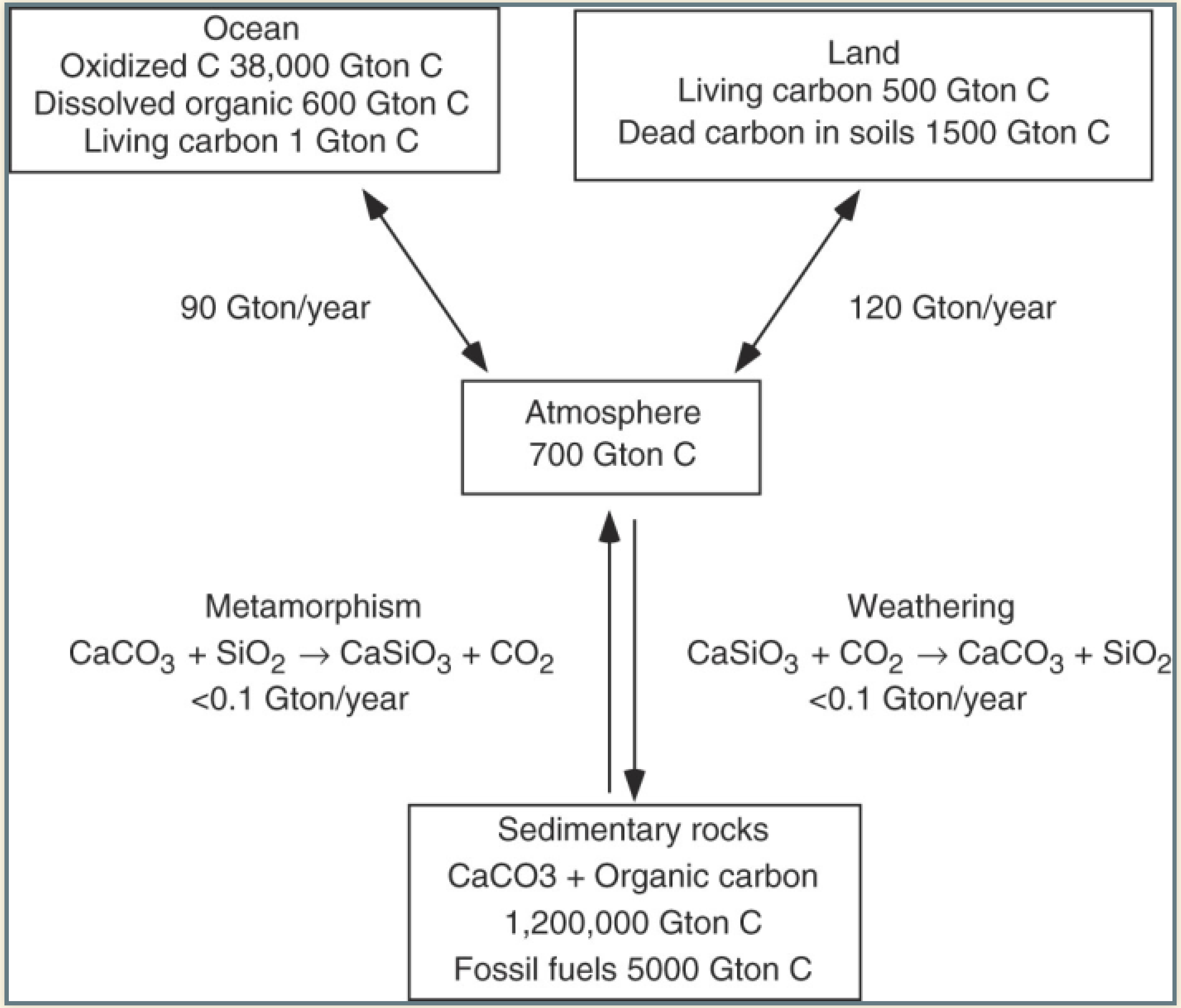
Source of CO_2: O_2 and ^{13}C



Source of CO_2: ^{13}C and ^{14}C



Where is Carbon



Carbonate/Bicarbonate Buffering

Buffering reaction

$$CO_2 + H_2O + CO_3^{2-} \rightleftharpoons 2HCO_3^-$$

Important points:

- Reaction goes both ways
- At equilibrium left and right are equal (balanced)
- Le Chatlier's principle
  - Add more of something on one side and balance shifts to the other side
  - Add more CO_2 and reaction converts CO_2 and CO_3^{2-} to HCO_3^-
- Lots more carbonate than CO_2 in ocean
  - Absorb lots more CO_2 because of buffering, carbonate
  - This consumes carbonate (CO_3^{2-})
  - Ocean acidification as carbonate is depleted

Weathering Reactions

Silicate Weathering Reactions

- Silicate Weathering (Urey Reaction)

$$CaSiO_3 + CO_2 \leftrightharpoons CaCO_3 + SiO_2$$

  - Intermediate (in water):

$$CaSiO_3 + H_2CO_3 \leftrightharpoons Ca^{2+} + SiO_3^{2-} + 2H^+ + CO_3^{2-}$$

  - Silicate rocks dissolve into ions in water
  - Wash into ocean
  - In ocean, living organisms convert ions to $CaCO_3$ and SiO_2.
  - Net result: Convert CO_2 from atmosphere into rocks at bottom of ocean.

Carbonate Weathering Reactions

- Carbonate Weathering

$$CaCO_3 + CO_2 \leftrightharpoons CaCO_3 + CO_2$$

  - Intermediate (in water):

$$CaCO_3 + H_2CO_3 \leftrightharpoons Ca^{2+} + 2H^+ + 2CO_3^{2-}$$

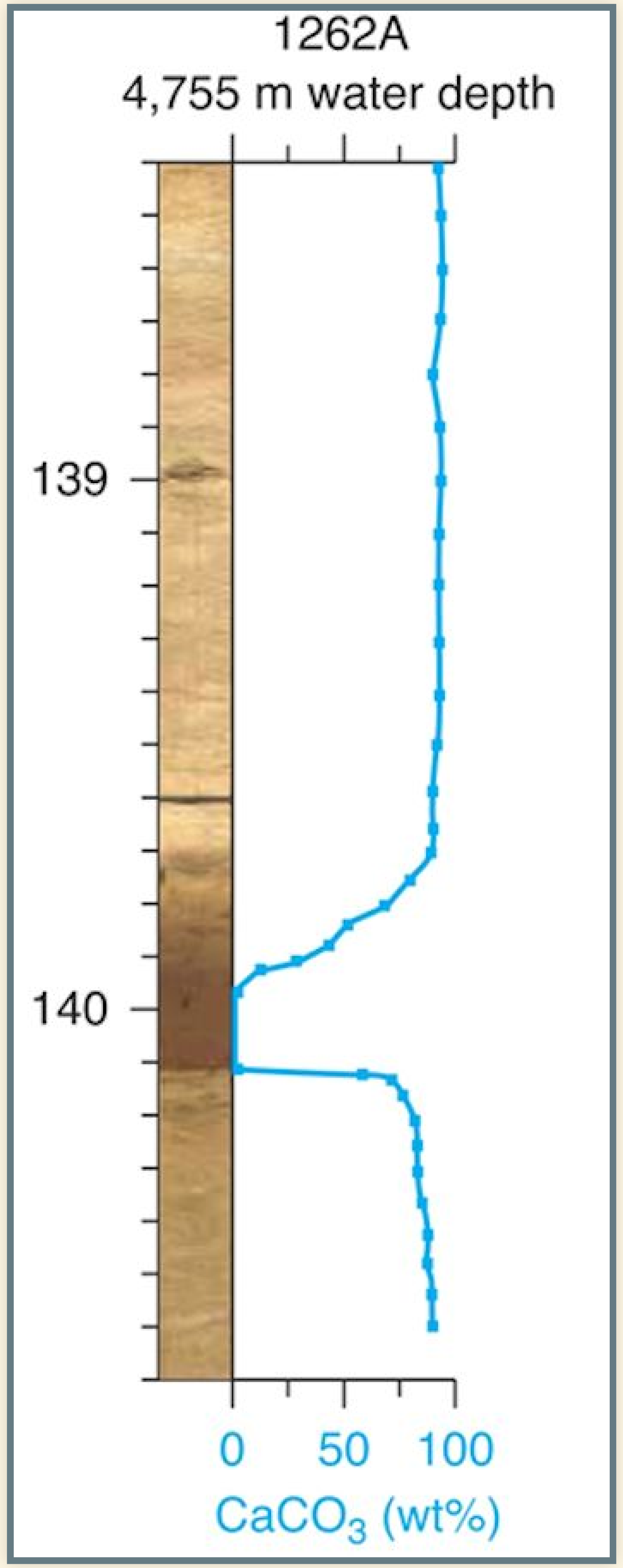
  - Carbonate rocks dissolve into ions in water
  - Add carbonate ions to oceans
  - Net result:
    - No permanent removal of CO_2 from atmosphere
    - But long-term storage in oceans.

Climates of the Past

- Paleocene-Eocene Thermal Maximum (PETM) (~55 million years ago)
- Pleistocene Ice Ages (~2.8 million to 10,000 years ago)
- Holocene (last ~10,000 years)
  - Medieval Warm Period (~1000 years ago)
  - Post-industrial warming

Paleocene-Eocene Thermal Maximum

- What was it?
- What important evidence do we see for what caused it?
- What is its relevance to today?



Pleistocene Ice Ages

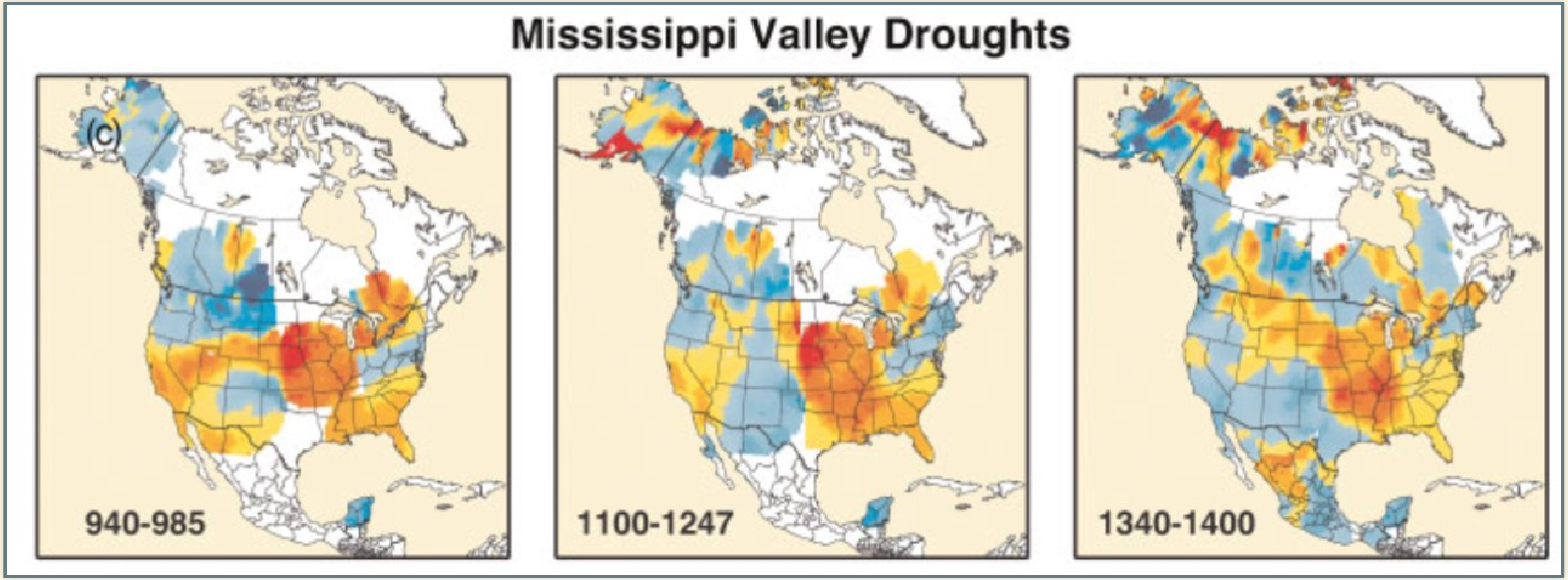
- What was it?
- What important evidence do we use to study it?
- What do we know about what caused it?
- What is its relevance to today?

Industrial-Age Warming

- What do we know about what caused it?
- What are some lines of evidence that human activity is responsible?

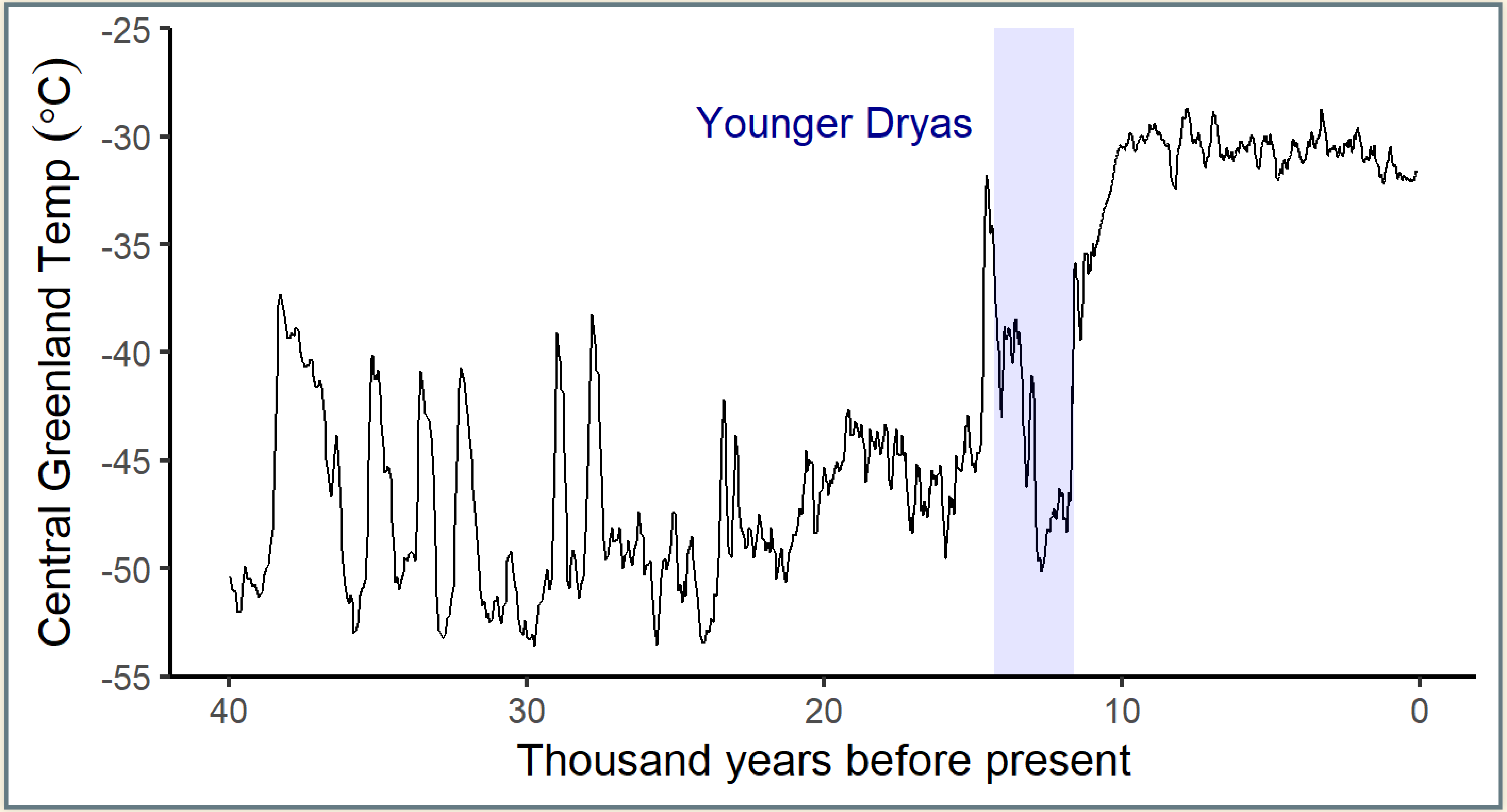
Medieval Warm Period

- What was it?
- What is its relevance to today?



Younger Dryas

- What was it?
- What is its relevance to today?



Global Ocean Conveyor Belt